wasted. The material has 1 to 10% hydrogen bonded to the Si, and is often designated as *a-Si:H*. The H atoms passivate a large number of the defects resulting from the incomplete bonding of the Si atoms. The atomic structure has no long-range order like all other crystalline or polycrystalline materials. This can be an advantage. Films are typically deposited between 150 to 300°C, the lowest temperature of any of the TFSC materials, allowing the use of lower-cost, low-temperature substrates. a-Si solar cells are deposited on glass, stainless steel foil, or plastic. The last two substrates are flexible allowing for "roll-to-roll" manufacturing where all the layers are deposited as the roll moves through their process zone. The *pn* junction is formed by doping the thin contact layers as they grow with dopant gases containing the boron or phosphorous atoms. All practical a-Si modules contain multiple junction devices where two or three junctions are grown on top of each other. This allows for more efficient utilization of the sunlight. The total thickness, including multiple junctions and all the contact layers, is less than 1 μm excluding the substrate. The highest reported efficiency was 15% for a triple junction, which degraded to about 13% before stabilizing. While a-Si TFSCs cells may have slightly poorer performance compared to other TFSCs when tested under laboratory conditions (Figure 1.8), they have a unique feature that improves their relative performance outside in real conditions; namely, their efficiency is temperature-independent while for all other PV technologies, c-Si or thin-film, the efficiency decreases as the module heats up as in real outdoor conditions. This can result in those other modules losing 2 to 4% (absolute) of their rated output in the summer time and helps a-Si look more favorable. The three major challenges for a-Si technology are: 1) to improve the efficiency from today's 6 to 8% up to 10 to 12%; 2) minimize or eliminate the self-limited degradation which reduces efficiency by 2 to 3% (absolute); and 3) to increase the deposition rate of the layers and the utilization of the gases to allow for faster, lower-cost manufacturing.

Polycrystalline layers of $Cu(InGa)Se_2$ (Chapter 13) alloys have produced the highest efficiency TFSC devices and modules. TFSCs based on $CuInSe_2$ (no Ga) achieved 12 to 15% efficiency but were limited by the low band gap. Alloying with Ga and/or S increases the band gap and increases the efficiency of delivering the electrons to the circuit (as discussed in Section 1.2). While many deposition methods have been explored in the laboratory, there are two different processes under commercial development. Co-evaporation forms the alloy by simultaneous evaporation of the Cu, In, Ga, and Se from sources onto a heated substrate. The other process is called *selenization*, because layers of Cu, In, and Ga are deposited by various means onto a substrate, then heated in the presence of Se from a gas such as H_2Se or a Se vapor, thus contributing the fourth constituent of the alloy. Substrate temperatures typically reach 500 to 600°C during some stage of the growth. Substrates of Mo-coated glass are typically used although metal foils or plastic are being investigated. The $Cu(InGa)Se_2$-films are *p*-type, typically 1 to 3 μm thick and have crystallites or grains on the order of 1 μm. The *pn* junction is formed by depositing an *n*-type layer of CdS, ZnO, or other new materials under development to replace the CdS. The highest reported cell efficiency is presently 19% and several companies have reported modules with $>10\%$ efficiency. However, progress has been largely empirical since little fundamental understanding of the materials or devices is available. A very active area of research is developing methods to incorporate other alloys to increase the band gap even further. The three major challenges for $Cu(InGa)Se_2$-related technology are: 1) to control the composition (Ga, S, Se, or Na) of the alloy through the film in a